ELECTRON MICROPROBE STUDY OF A CRATER AND EJECTA PRODUCED BY HYPERVELOCITY IMPACT AGAINST A Ni-Fe TARGET

Richard A. Schmidt, Klaus Keil, and Donald E. Gault

National Aeronautics and Space Administration
Space Sciences Division
Ames Research Center, Moffett Field, California

ELECTRON MICROPROBE STUDY OF A CRATER AND EJECTA PRODUCED BY HYPERVELOCITY IMPACT AGAINST A Ni-Fe TARGET

ABSTRACT

The electron microprobe, an instrument that permits nondestructive quantitative chemical analyses to be performed in micron-sized areas, was employed to study a crater and the ejecta produced by the impact of a Ni-Fe steel projectile against a target of the same composition. Apart from a thin layer on the inside of the crater, no change in the target was noted. However, small, black, magnetic spherules recovered in the ejecta from the crater reveal significant chemical modifications.

ELECTRON MICROPROBE STUDY OF A CRATER AND EJECTA PRODUCED BY HYPERVELOCITY IMPACT AGAINST A Ni-Fe TARGET

INTRODUCTION

Hypervelocity impact experiments are commonly confined to the study of cratering mechanics and little consideration is given to possible chemical changes produced in the deformed material around a crater or in the ejecta. The chemistry and structure of ejecta and other shock-loaded products of impact events are, however, of special significance to workers in the geosciences who are concerned with problems of formation of meteorite craters, modification of meteorite bodies, and production of "cosmic dust." The experiment described in this paper was carried out as part of a more general program of research at Ames Research Center devoted to the study of impact in rocks and minerals, and was an attempt to simulate the formation of cosmic dust. Although the results of the experiment are not directly applicable to the study of the terminal ballistics of hypervelocity projectiles, the study of chemical changes in shock-loaded materials by electron microprobe techniques should be valuable in achieving a better understanding of impact processes.

EXPERIMENTAL PROCEDURE

The experiment was conducted at the light-gas-gun facility of the Ames Research [illegible] Hypervelocity [illegible]

Range. A cylindrical Ni-Fe steel projectile (AISI No. E-2512), 0.32 cm in diameter, 0.21 cm long, and weighing 0.1223 gm was propelled against a 5 cm × 5 cm × 2.5 cm target of the same composition. This material was chosen because it most closely approaches the composition of iron meteorites. The experiment was carried out in air at an ambient pressure of 75 mm of mercury (about 0.1 atm). Velocity of the projectile at impact was about 5.6 km/sec^{-1}, and peak impact pressure is estimated by means of one-dimensional shock wave theory to have been about 1.8 megabar. The event took place in a plastic box especially built to retain the ejecta from the crater for study. A view of the plastic box is shown in Figure 1. At the right in the box is the target block which was knocked over by the force of impact. At the left is the polystyrene foam layer for catching the ejected material. The darker circle in the polystyrene is the locus of the points of impact of the ejected particles.

ANALYTICAL METHOD

Both target and ejecta were analyzed with an electron microprobe. This instrument directs a finely focussed (1 micron diameter) beam of high energy electrons at the specimen. The electron beam excites an X-ray spectrum consisting of a continuous background spectrum and the characteristic X-rays of the elements present in the target. This spectrum is then analyzed for wavelength and intensity with the aid of curved crystal detection systems. To a first approximation, the intensities of the characteristic X-rays at discrete wavelengths are proportional to the amounts of the various elements present. Thus, a nondestructive, quantitative chemical analysis can be performed in micron-sized areas. (For a detailed description of the principles and techniques of electron microprobe analysis, compare Birks.[1]) In the present study an Applied Research Laboratories electron microprobe X-ray analyzer was used. The instrument is equipped with three dispersive channels, and thus allows measurement of three different elements at the same time and on exactly the same spot in the surface of the sample. In the quantitative analyses, pure elements were used as standards for the determination of Mn, Cr, and Ni. For Fe, both pure Fe and a chemically analyzed magnetite (Fe_3O_4, Fe = 72.4%) were used as standards; for S, the standard was chemically analyzed pyrite (FeS_2, S = 53.60%); while for P, the standard was apatite (P = 18.2%). Corrections were made for wavelength shift, detector dead time, background, mass absorption, secondary fluorescence, and atomic number. The measurements were made with 20 kv electrons and up to 200 seconds of integration time.

Care is necessary in preparing samples for electron microprobe analysis because surface irregularities on specimens can cause unpredictable absorption effects and thus yield spurious results. The crater produced by impact was sectioned, mounted in epoxy, and polished with successively finer abrasives to yield a flat, smooth, mirror-like finish. Smaller ejecta particles were embedded in clear plastic and polished in the same manner. The sections were vacuum coated with a layer of carbon a few hundred angstroms thick in order to make them conductive.

RESULTS

The sectioned and polished crater is shown in Figure 2. Cavities produced by mechanical deformation of the steel upon impact may be seen at the base of the crater. In addition, microscopic lamellae generally parallel to the outline of the crater were observed in polarized light at high magnifications. (It was not possible to secure usable photographs of those features.) In spite of these marked physical changes resulting from impact, electron microprobe analyses of the block containing the crater are identical with those for an unshocked piece of the same material (Table I). Apart from a thin (of the order of a few microns) layer on the interior of the cavity, no change in the target material was noted.

However, significant chemical modifications are revealed in small, black magnetic spherules recovered in the ejecta from the crater (Figure 3). The spherules range in diameter from 20 to about 100 microns, are hollow with walls of varying thickness, and are comprised primarily of magnetite (Fe_3O_4). In Table I, the results of the electron microprobe analyses of a spherule are compared with the analyses of the original steel target block and with the steel in the immediate surroundings of the crater. It is apparent that considerable chemical fractionations occurred as the spherules were formed. These are the following:

a. The original metallic nickel-iron (94.2% Fe) was oxidized to magnetite in the process of spherule formation and contains 72.1% Fe.

b. In the original steel target the nickel is homogeneously distributed throughout the sample and averages 5.17% Ni. The nickel is still homogeneously distributed in the spherule produced by impact but its concentration is depleted by an order of magnitude to about 0.5% (Table I). This is the most significant chemical fractionation that took place in the process of spherule formation.

c. The original target steel contains 0.27% Si homogeneously distributed throughout the sample. In the spherule, however, the Si is enriched in irregular patches up to about 10 microns wide and up to 30 microns long (Figures 4 and 5). The main mass of the magnetite, however, has been depleted in Si and contains only 0.05% Si.

d. Chromium seems to have been depleted in the spherule in comparison to the original target material (Table I).

e. The other minor elements studied (Mn, Cu, S) seem not to have fractionated notably in the process of spherule formation.

DISCUSSION

The lack of appreciable chemical changes in the target block itself indicates that nearly all the energy of impact was consumed in mechanical deformation of the steel and in ejection of material from the crater. It would appear, at least for events of the scale investigated, that chemical modifications of the residual target material from an impact are negligible. The same appears to be true for most of the ejecta from the crater. About 75 percent of particles recovered are angular fragments and flakes which suffered only physical modification.

The remaining one-quarter of the ejecta are the black spherules, which differ considerably in chemical composition from the original target material. Spherules are a form that may be assumed only by a true liquid, and indicate that this portion of the ejecta was subjected to temperatures in excess of about 1500° C, the melting point of iron. The presence of magnetite as the principal constituent of the spherules indicates clearly that extensive oxidation of iron occurred in this portion of the ejecta from the crater.

A mechanism of spherule formation is suggested as follows: (1) Virtually instantaneous, irreversible shock heating of the target and projectile material by the impact, melting a portion of the ejecta. It is estimated, based on one-dimensional shock theory, that temperatures in excess of 1500° C must have been attained. (2) Oxidation of the liquid ejecta by the oxygen present in the collection chamber. The strong exothermic reaction by which magnetite is formed from iron would further raise the temperature of the melt to, perhaps, almost 3000° C, past the boiling points of the metals. Magnetite would not vaporize appreciably at the probable temperatures attained, according to Margrave's[2] thermochemical tables for high temperatures. However, nickel oxides are not stable under the experimental conditions. It therefore appears likely that nickel was lost from the droplets by vaporization. Segregation of silicon into patches probably was induced by the formation of an iron silicide in these areas, as suggested by the elemental distributions. (3) Quenching of the droplets to spherules. Further work on aspects of this problem is in progress.

ACKNOWLEDGEMENTS

This work was supported in part by National Academy of Sciences - National Research Council Resident Research Associateships to K. Keil and R. A. Schmidt. We express our thanks to Mr. Ezra Heitowit for assistance in the shock experiments.

REFERENCES

1. Birks, L. S. (1963) Electron Probe Microanalysis, Volume XVII, Series on Chemical Analysis, Interscience Publishers, N. Y.

2. Margrave, J. L. (1959) Thermodynamic calculations at high temperatures, in Physico-chemical Measurements at High Temperatures, Bockris, White, and Mackenzie, Editors, Academic Press, N. Y., p. 353-368.

TABLE I.- COMPARISON OF THE AVERAGE COMPOSITIONS OF THE STEEL TARGET WITH THE IMPACT-PRODUCED SPHERULE, AS OBTAINED BY ELECTRON MICROPROBE TECHNIQUES

Sample	Number of electron microprobe analyses	Concentration of elements, in weight percent										
		C	Si	P	S	Cr	Mn	Fe	Ni	Cu	Mo	Total
Original target and projectile material. Steel AISI E-2512. Composition according to Coulter Steel and Forge Company	---	0.11	0.29	0.008	0.014	0.02	0.52	93.908*	5.01	0.09	0.03	100.000
Original target and projectile material, steel AISI E-2512	70	n.d.	0.27	n.d.	0.01_3	0.05_9	0.64	94.2	5.17	0.02_5	n.d.	100.377
Target block after cratering experiment. Approximately 2 cm away from crater	72	n.d.	0.24	n.d.	0.01_5	0.05_4	0.70	94.2	5.07	0.02_3	n.d.	100.302
Target block after cratering experiments in the immediate vicinity of the crater	85	n.d.	0.26	n.d.	0.01_3	0.06_0	0.64	94.3	4.97	0.02_5	n.d.	100.268
Impact produced spherule (magnetite)	155	n.d.	0.05	n.d.	0.01_3	<0.01	0.55	72.1	0.51	0.01_8	n.d.	---

*Calculated value.

CAPTIONS

Figure 1.- Experimental apparatus. At left, polystyrene foam layer used to trap the ejecta from the crater. The ejecta occur in the darker-colored circular area. At right, the nickel-iron steel target after impact.

Figure 2.- Polished section through crater in target.

Figure 3.- Polished section through spherule ejected from target.

Figure 4.- Portion of a polished section of a spherule under high magnification. Note dark gray patches.

Figure 5.- Electron beam scanning photographs of Si-rich areas in the spherule produced by hypervelocity impact. The pictures were taken as the electron beam swept over a microscopically selected area in the sample and recording the signals from the counters on oscilloscope screens. BSE is backscattered electron image. Ni, Si, Fe are pictures obtained in the Kα radiations of these elements. The Si image shows an enrichment of Si in patches. The dark areas in the left part of the BSE image correspond to these patches, indicating that their atomic number is lower than that of the surrounding magnetite. Some of the dark areas in the upper portion of the BSE image are surface irregularities. Fe and Ni appear to be homogeneously distributed throughout the sample.

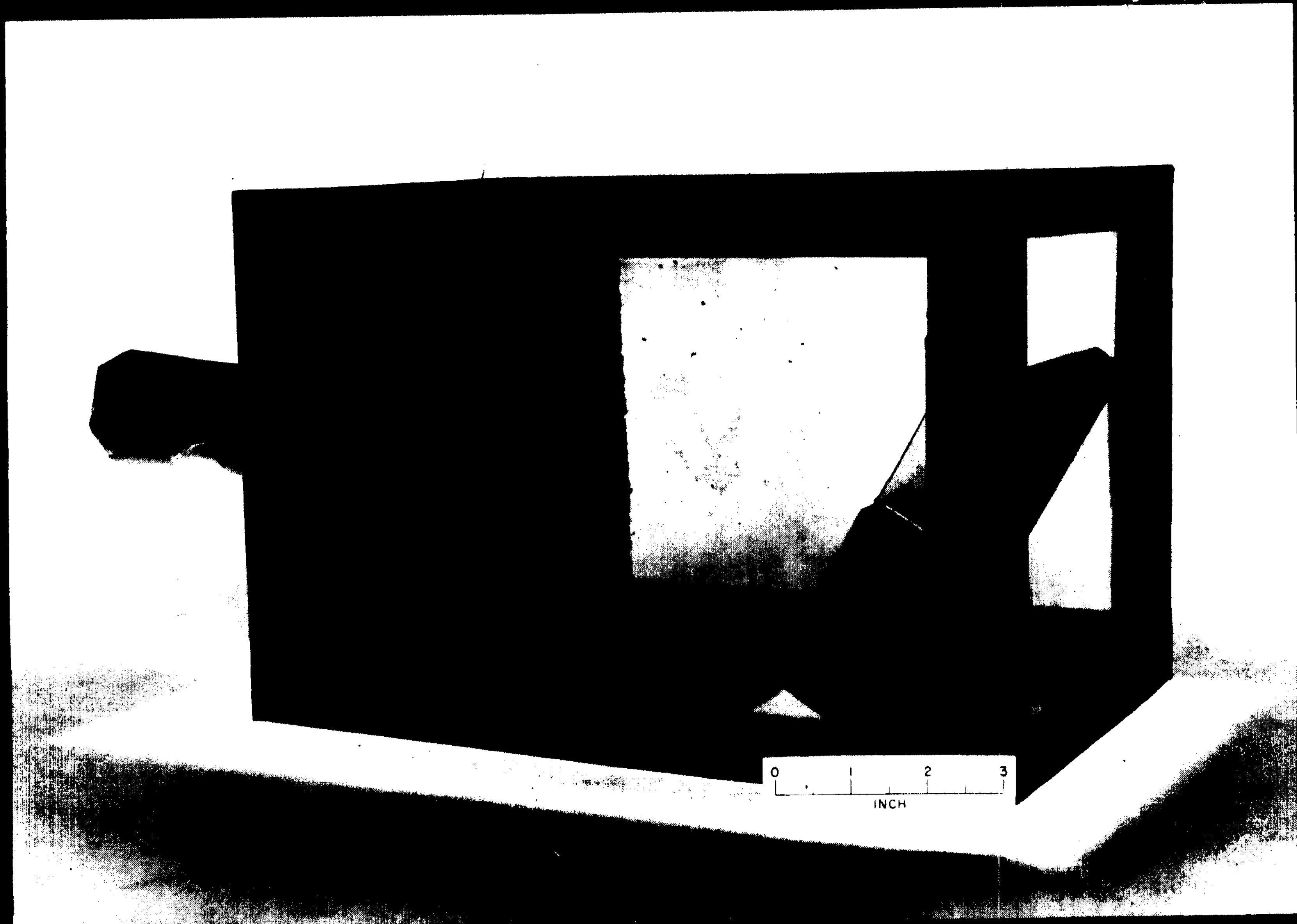

Figure 1.

Figure 6.

AP 129 1

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

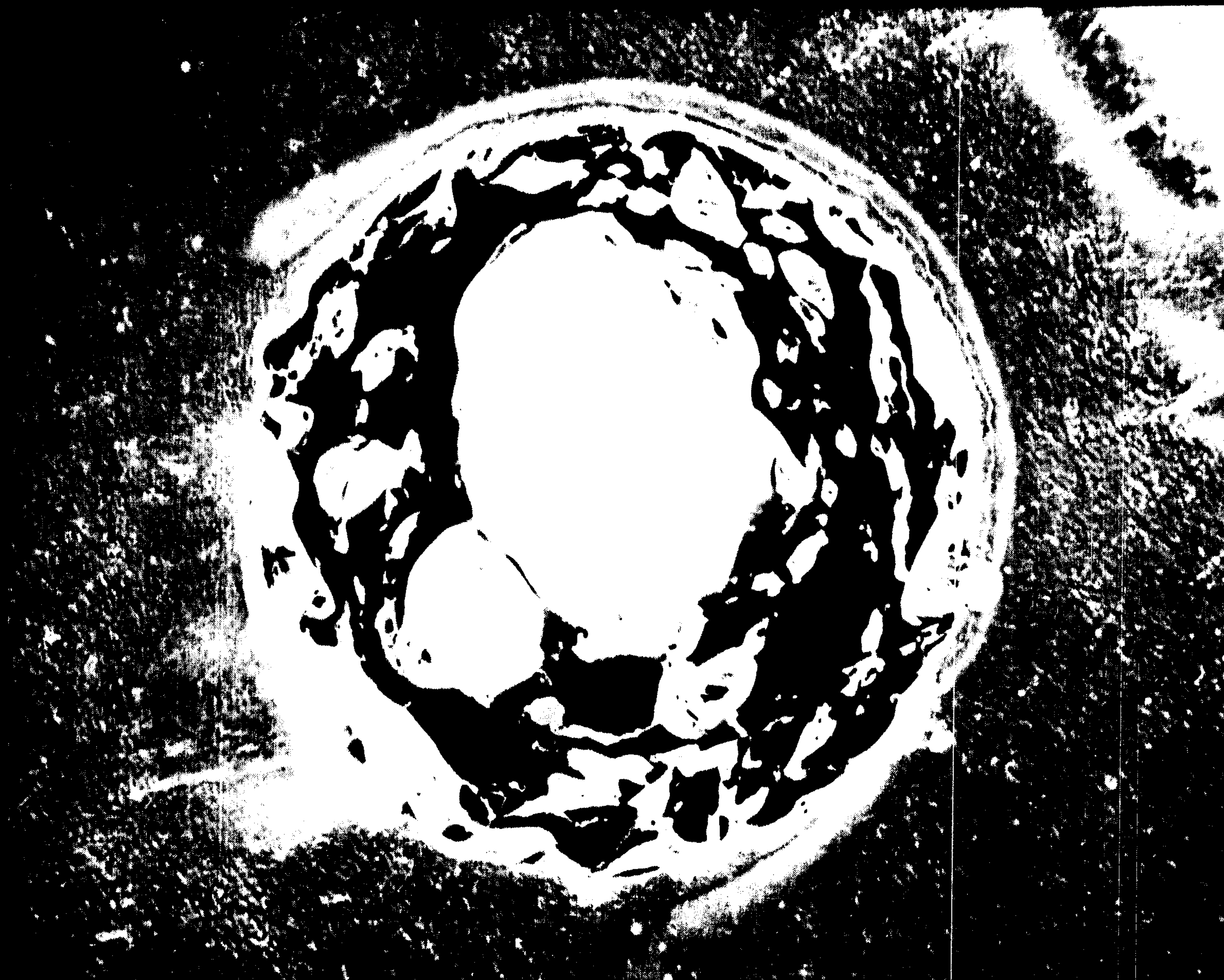

Figure 3.

AP 132

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

Figure 4.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

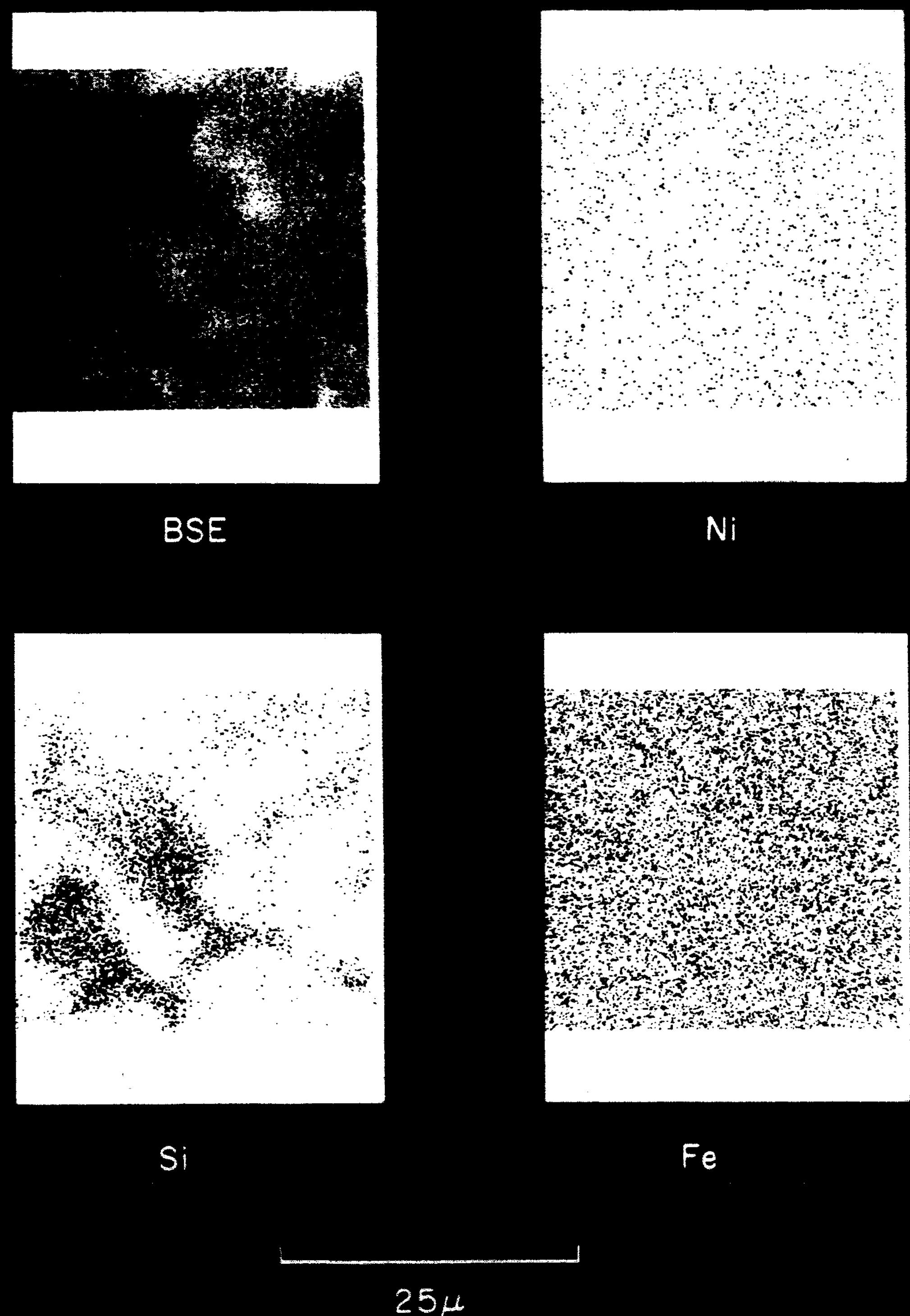

Figure 7.